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Citation: [AIP Conf. Proc.](#) **1539**, 116 (2013); doi: 10.1063/1.4811002

View online: <http://dx.doi.org/10.1063/1.4811002>

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Solar Energetic Particles and their Variability from the Sun and Beyond

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Abstract. With the onset of solar cycle 24 activity STEREO and near-Earth spacecraft are now measuring many multi-spacecraft solar particle events. We present examples of time-intensity distributions, energy spectra, fits to longitude distributions, a combined imaging/in-situ study, and MHD modeling of one event. Implications of these new results are discussed.

Keywords: Solar energetic particles, particle acceleration, coronal mass ejections

PACS: 96.50.Vg, 96.60.Vg, 96.60.ph, 96.60.qe, 96.60.Q-

INTRODUCTION

After an extended solar minimum lasting through early 2010, solar cycle 24 is now well underway, beginning with the first GOES-class solar energetic particle (SEP) events in mid-2010 (Figure 1). The cycle-23 maximum provided opportunities to observe SEP events near Earth and at high latitude with Ulysses; cycle 24 is the first with a 360°-longitudinal view of the Sun, provided by NASA's twin STEREO spacecraft and an array of very capable near-Earth *in-situ* and imaging instruments. In this paper we report examples of SEP events measured from three separate points of view, and discuss several other aspects of solar energetic particle variability.

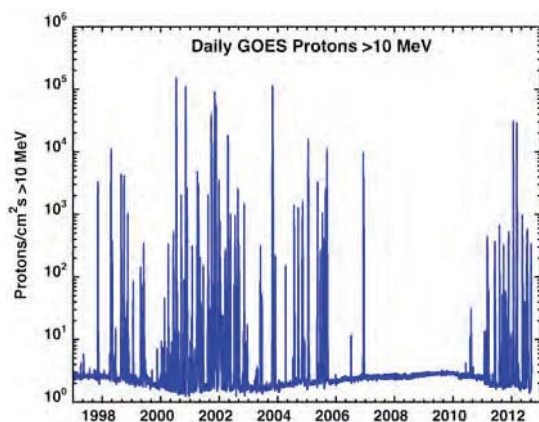


FIGURE 1: Daily-average >10 MeV proton intensities measured by the NOAA GOES satellites from 1997 through mid-2012. The underlying background is due mostly to galactic cosmic rays.

Following the deepest solar minimum in ~ 100 years there have been suggestions that the Sun may be moving into a phase of minimum solar activity as experienced in ~ 1700 , ~ 1800 , and ~ 1900 . It is therefore of interest to compare the SEP output of cycle 24 with that of previous cycles. Figure 2 compares integrated fluences of >10 MeV protons during Solar Cycles 22, 23, and 24, starting at solar minimum. It is interesting that as of 1 September 2012, cycle 24 was ahead of the pace of cycle 23. However, to maintain this pace there must be one or more large SEP events by the end of 2012.

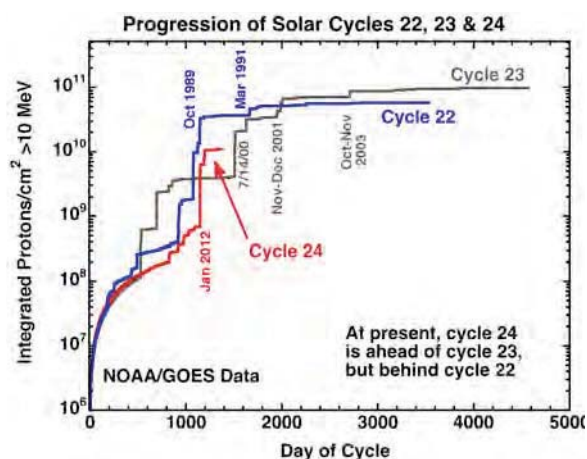


FIGURE 2: Integrated fluence of >10 MeV protons versus the day of the cycle for solar cycles 22, 23, and 24 (starting in September 1986, May 1996, and December 2008, respectively). Also indicated are the approximate dates of major solar proton events. Based on data from NOAA/GOES satellites.

Solar Wind 13

AIP Conf. Proc. 1539, 116-121 (2013); doi: 10.1063/1.4811002
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In mid 2010, when SEP activity began to pick up, STEREO-A and STEREO-B (hereinafter STA and STB) were separated by $\sim 145^\circ$. By the time of Solar Wind 13, the separation had grown to $\sim 235^\circ$. Thus, the STEREO, and near-Earth instruments have provided the opportunity to explore the longitudinal dependence of SEP intensities, fluences, onset times, composition, and energy spectra as cycle 24 builds to a maximum. In this paper we present examples of SEP time intensity profiles, fluences, and energy spectra as a function of longitude, including fits to the longitude dependence of several events. Also presented is a 3D MHD model of one event. In related work, there have been other multi-spacecraft studies of cycle-24 SEP events [1,2,3] and studies of multi-spacecraft composition variations [4].

OBSERVATIONS

The STEREO SEP observations presented here are from the SIT [5], LET [6] and HET [7] sensors on STA and STB, which collectively measure protons from ~ 0.3 to 100 MeV. Near-Earth SEP measurements are from the ULEIS [8], EPAM [9], and SIS [10] instruments on ACE; the EPHIN [11] and ERNE [12] instruments on SOHO; and the EPI sensors [13] on the GOES satellites. CME data are from the SECCHI instruments [14] on STA and STB and SOHO/LASCO [15].

Multi-Spacecraft SEP Observations

We focus here on examples of large SEP events observed at 3 separated locations. An interesting example is the 3 November 2011 event that originated on the far side of the Sun at E155 [16]. Figure 3 (top) shows the spacecraft positions; note in the middle panel that the intensities rose very rapidly (within ~ 30 min of each other) at all spacecraft. STA recorded the highest intensities 103° east of the eruption. The next best connection was apparently to STB, 53° west of the eruption. Near-Earth sensors recorded lower intensities, except at ~ 100 MeV. The measured fluence spectra (bottom) are surprising in that the spectral slopes bear little apparent relation to each other.

Spectral Variations

Aside from Van Hollebeke et al. [17] there has not been much work on the dependence of SEP energy spectra at 1 AU on the longitude of the source region. In Figure 4 we show examples of SEP fluence spectra at three well-separated points. It is surprising that the spectra sometimes have similar shapes at all three points (e.g., 4 August 2011), while in other events

there are major differences (e.g., 27 January 2012, 21 March 2011, and 3 November 2011 in Figure 3). Such spectral differences may reflect the effects of variations in shock geometry (quasi-perpendicular

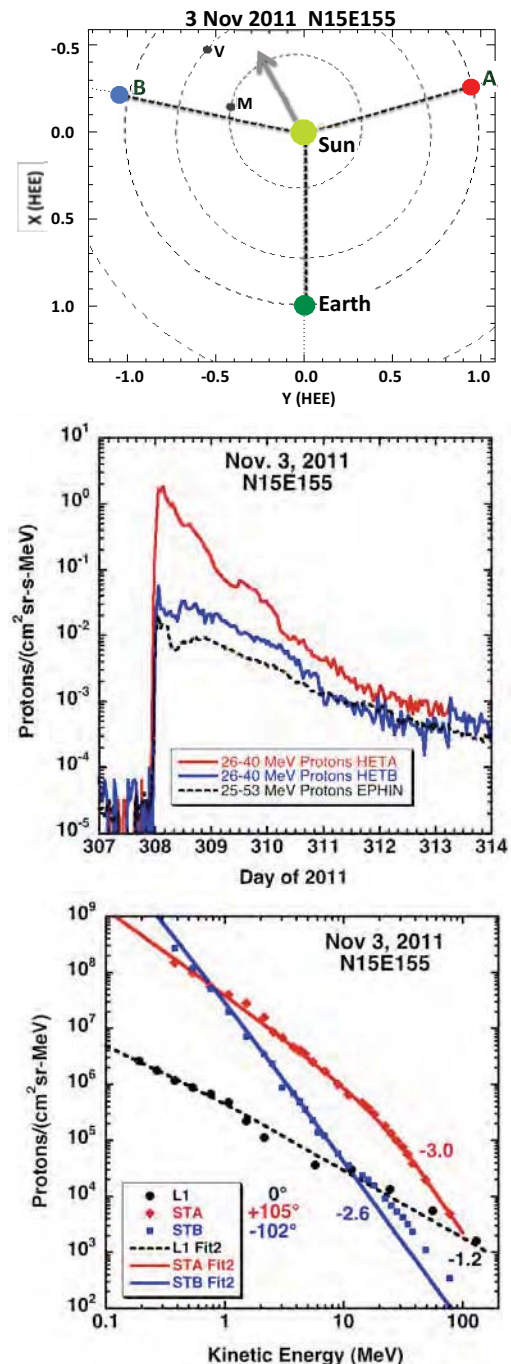


FIGURE 3: (top) Spacecraft and planet locations for the 3 Nov 2011 SEP event originating at N15E155 (arrow indicates CME direction). (middle) Time-intensity distributions of ~ 26 -40 MeV protons at STA, STB and SOHO. (bottom) Fluence spectra from STA, STB, and near-Earth spacecraft show a wide range of spectral indices.

shocks may produce harder spectra than quasi-parallel shocks [18,19], longitude-dependent mixes of flare and shock-accelerated particles [20], or differences in the density and spectra of seed particles encountered by the shock.

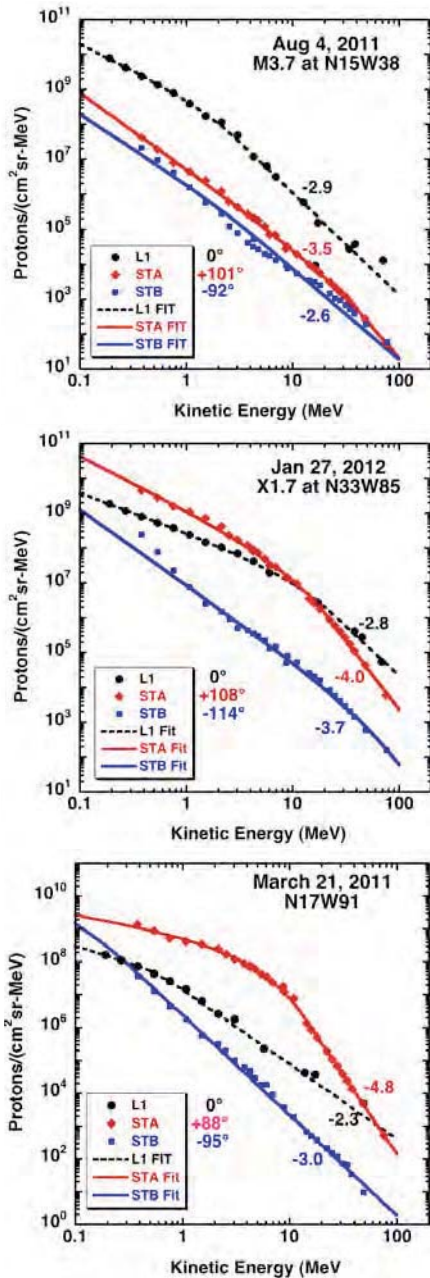


FIGURE 4: Proton fluence spectra from STA, STB, and near-Earth spacecraft for three large SEP events. (Top): 4 August 2011 (Middle): 7 January 2012; and (Bottom): 21 March 2011. The measured spectra are fit with the double power-law function of Band et al. [21] and the high-energy slopes are indicated. Also shown are the source locations and the heliographic longitudes of the spacecraft.

SEP Intensity Variations with Longitude

One key goal of the STEREO mission is to characterize and understand longitudinal variations in the intensity and energy spectra of SEP events. Although the long solar minimum delayed this opportunity for ~ 2 years, the onset of new activity in 2010 and 2011 included a number of events observed essentially all of the way around the Sun.

Earlier studies described SEP longitude distributions based on single-point measurements. Most were based on an exponential dependence on the longitude difference of the observer from the source location, sometimes with an offset (e.g., [22, 23, 24]). Lario et al. [25] were the first to use multi-spacecraft data to obtain fits to both the longitudinal and radial dependence of SEP transport. They fit Helios 1 & 2 and IMP-8 data in two energy intervals with a Gaussian distribution, offset somewhat to the east from the best solar-wind connection to the source region, as illustrated in Eqn. 1 for proton fluences (F).

$$F = F_0(R/a)^n \exp[-k(\phi - \phi_0)^2] \quad (1)$$

Here R is radial distance, $a = 1$ AU, and ϕ is longitude. For 27 – 37 MeV protons they obtained best-fit values of $n = -1.15 \pm 0.24$, $\phi_0 = -18.1^\circ \pm 3.9^\circ$, and $k = 1.04 \pm 0.06 \text{ rad}^{-2}$ (see also [26] for recent results based on ACE, SOHO, and Messenger data).

Figure 5 shows examples of fits to near-Earth data using Eqn. (1). The top two panels include fits to 26–40 MeV proton fluences as well as the mean 27–37 MeV distribution obtained by [25] fitting many events, normalized to the fluence maximum and flare location. The bottom panel has fits to 4–10 MeV proton peak intensities compared to the average 4–13 MeV distribution from [25]. In our fits latitude differences between the source and observer were also accounted for using the same exponential function, peaking at the flare latitude. The fits performed to date typically favor somewhat broader Gaussian distributions than found by Lario et al. [25], possibly because the measurements are, on average, further from the Sun. The nominal 4–13 MeV longitude distribution has also been used in evaluating the SEP energy content of 20 large SEP events from solar cycle 23 [27].

The 3 November 2011 event (Fig. 1) brought home the fact that so-called “far-side” events (not visible from Earth) can contribute large fluences to near-Earth spacecraft (see also [28]). Of 11 GOES-class events observed so far during solar cycle 24, STEREO data show that two originated on the far side of the Sun. Undoubtedly, far-side events have always played a role in space weather at 1 AU.

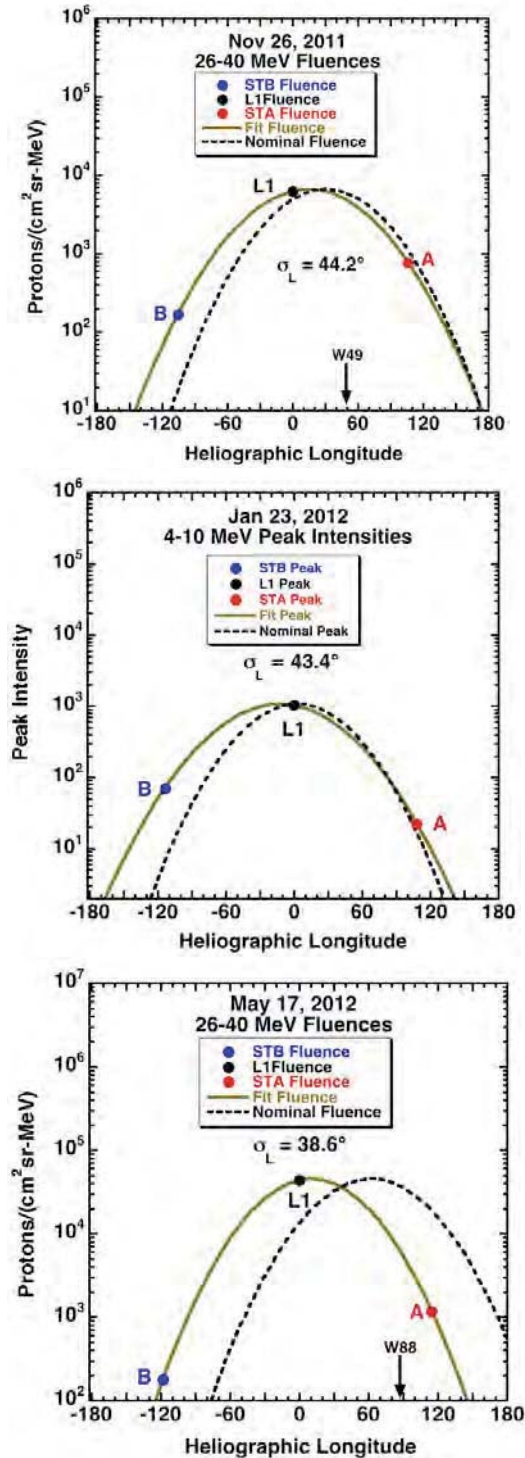


FIGURE 5: Examples of fits (solid curves) to 3-point longitude distributions measured by STA, STB, and SOHO/EPHIN using the Gaussian function of Lario et al. (see text). Also shown (dashed) are nominal distributions [25] for 27-37 MeV protons (top and bottom panels) and for 4-13 MeV proton peak intensities (middle panel). The 26-40 STEREO data are from HET and the 4-10 MeV proton intensities are from LET. Flare locations are indicated.

SEP and Imaging Observations

STEREO and near-Earth assets have provided new opportunities for multi-point in-situ and imaging studies of solar eruptions. The 21 March 2012 event originated at W117° with STA and STB at W88° and E95°, respectively. STA/SECCHI and SOHO/LASCO observed a fast CME early on March 21, surrounded by an electron cloud. STA recorded the expansion of an EUV disturbance that tracked the lateral expansion of the CME-driven shock, and determined its distance from the CME source location versus time (see Figure 6 and Rouillard et al. [29]). Standard velocity dispersion analysis using STA data determined an SEP release time near the Sun of $2:27 \pm 0.03$ UT, substantially earlier than found by the SOHO ERNE and EPHIN sensors at L1 ($2:57 \pm 0.05$ UT), but generally consistent with the arrival times of the CME shock at the magnetic footpoints of STA and L1. Thus the onset at L1 was delayed until the shock reached the footpoint of the L1 field line.

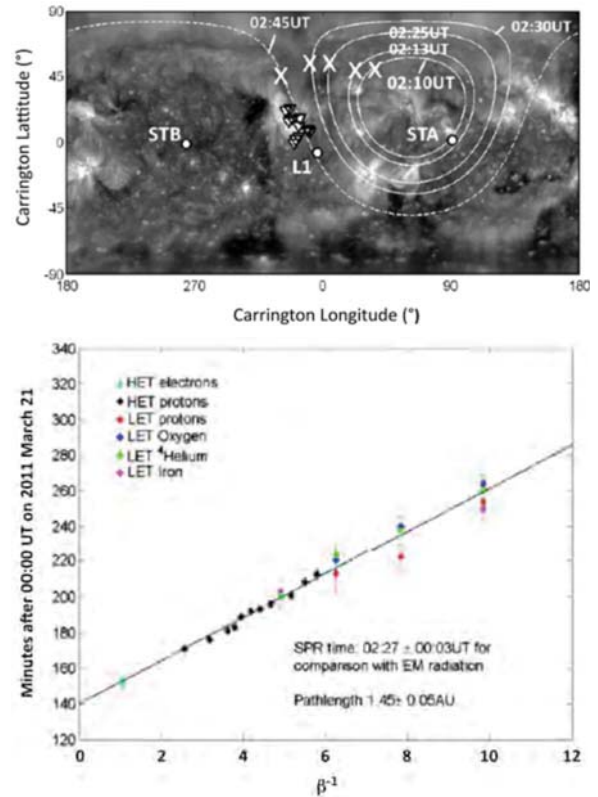


FIGURE 6: (Top): Carrington map of 195Å EUV observations on 21 March 2011 by SECCHI/STA shows the evolution of an EUV disturbance from the CME source location assuming the wave expands uniformly in all directions. The magnetic foot-points connected to STA, L1, and STB are indicated. (Bottom): Velocity dispersion analysis of electrons, protons, and heavy ions observed by the LET and HET sensors on STA gives a solar particle release (SPR) time of $02:27 \pm 0.03$ UT and a pathlength of 1.45 AU. Figures from Rouillard et al. [29].

CME and SEP Modeling

The interpretation of multi-point measurements of SEP evolution can be greatly aided by global models of the associated ICMEs, shocks, and key solar wind parameters. The time-dependent 3D MHD ENLIL cone model [30] is widely used by NASA and NOAA to forecast the evolution and arrival of ICMEs and associated solar wind and shock parameters. This model can be extended to include solar energetic particle acceleration and transport with the SEPMOD model [31].

The large 27 January 2012 event that erupted at 1856UT at W85° is of interest because it was observed at Mars as well as STEREO and L1. Indeed NASA's MRO mission experienced an instrument anomaly during this event [32]. Figure 6 (top panel) shows ENLIL/Cone results for this event at ~00UT on 30 January when the shock was predicted to pass Earth (there appears to have been a shock at ACE at ~1540U on the 30th). The middle panel of Figure 6 shows the predicted arrival of SEPs at Earth just before 24:00UT on 27 January. SEPs actually arrived at ACE at ~18:45UT, ~5 hrs earlier (bottom panel). There was no report of an ICME at Earth [33].

Note that Mars was better connected to the shock than was Earth. The model arrival of SEPs at Mars (not shown) was ~0300UT on 28 January. ASPERA first observed SEPs at Mars late on 27 January, also earlier than predicted. Possible causes of the earlier SEP arrival times are discussed below.

DISCUSSION AND SUMMARY

In this paper we have presented several examples of multi-spacecraft SEP events observed at STEREO and near-Earth. The four examples of proton energy spectra are interesting in that there is wide divergence in spectral slopes for the same event. For the three events in Figure 4 it appears that L1 should be best connected to the source region, and in each case the L1 energy spectrum above the spectral break is as hard or harder than the others, but for the 3 Nov 2011 event in Figure 3 STA is best connected, but the L1 spectrum is the hardest at high energies. It will require a more complete survey of multipoint spectra to delineate any pattern(s) of how energy spectra vary with longitude, and whether these spectral variations relate to other parameters such as CME characteristics and/or shock geometry.

Thanks to STEREO, it is now clear that far-side events make a significant contribution to the near-Earth SEP fluence. Indeed, it is rather surprising that so many events are observed at 3 well-separated points. This also provides evidence for yet another

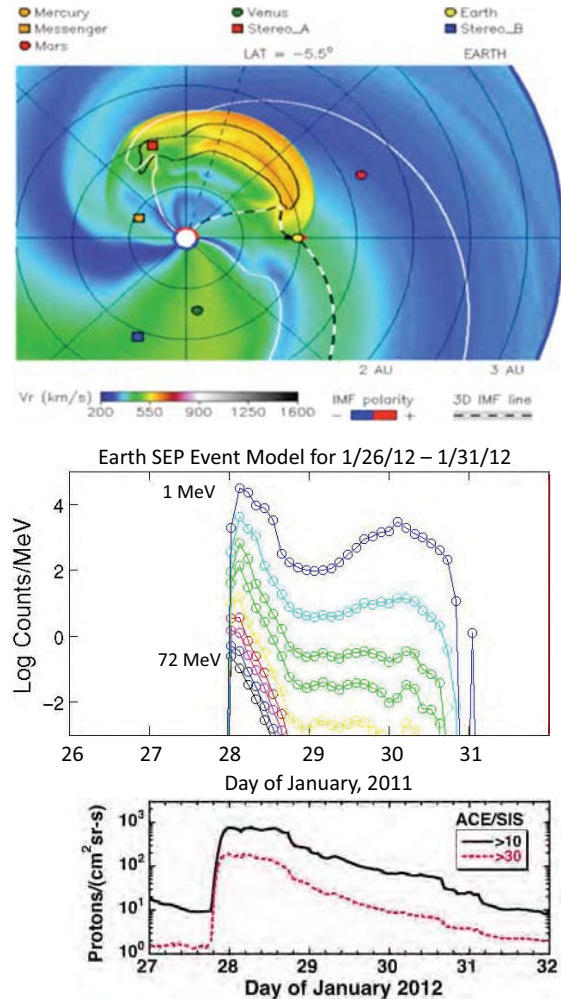


Figure 6 (Top): ENLIL model of the Jan 27, 2012 solar eruption showing the CME when the shock first reached Earth. Also shown is the field line that Earth is on (black-white line) and the locations of STA, STB and the inner planets. (Middle): Intensity of 1 to 72 MeV protons from the ENLIL model. (Bottom): Intensity of >10 and >30 MeV protons measured by ACE/SIS.

source of seed-particles that can be accelerated by a subsequent CME.

The Gaussian distribution used by Lario et al. [25] to characterize SEP longitudinal variations appears to provide reasonable fits to STEREO and near-Earth data, although the best width and offset parameters (k and ϕ_0 in Eqn. 1) may differ from those for Helios and IMP-8 data. In particular, the Gaussian distribution provides a reasonable representation of the fact that near the line of best connection to the source region, the distributions are reasonably independent of longitude. It is also clear that there are significant event-to-event variations in both the width of the measured distributions, and in the offset from the best connection location. With a larger sample of events it

will be interesting to see whether event-to-event differences can be related to other measured parameters such as CME characteristics (speed, width, non-radial direction), or to solar wind properties.

The study of Rouillard et al. [29] demonstrates clearly that newly accelerated particles do not generally appear on a field line until that field line is connected to the shock. On the other hand, in the 3 November 2011 event it is observed that SEPs can very quickly (within ~30-45 minutes) make their way all around the Sun.

From these and other observations [1,35] it appears that SEPs are distributed in longitude more easily than expected. For example, Wiedenbeck et al. [35] observed particles from a small impulsive solar flare over 136° in longitude. Assuming a point source, Giacalone and Jokipii [36] suggested that cross-field diffusion could explain those observations if the ratio of the perpendicular and parallel diffusion coefficients was $K_\perp/K_\parallel \approx 0.01$. They also pointed out that corotation effectively transports particles to the east. Other suggested explanations included the longitudinal spreading of field lines from an active region and distortion of the interplanetary magnetic field by a previous CME [35]. Of course, in the events described in this paper the width of the CME shock can play a key role in distributing particles in longitude. It will require the study of a larger sample of events to understand the relative importance of these processes.

An initial comparison of SEP arrival times at Earth and Mars with the WSA-ENLIL-Cone-SEPMOD model shows qualitative agreement, but particles apparently reached both Earth and Mars earlier than in the model (in fairness, the results in Figure 6 were based on a preliminary CME speed of 1600 km/s; the SOHO/LASCO CME site later listed 2500-3000 km/s). As discussed above, SEPs do not generally populate a given field line until the shock reaches that field line. For a source location at $W85^\circ$ the shock was unlikely to be connected to Earth immediately, introducing a delay into the arrival time of SEPs at 1 AU. The modeled delay is increased if the CME speed in the model is underestimated.

In any case, it is hoped that models such as these will be a significant aid in interpreting complex, multi-spacecraft measurements like those presented here.

ACKNOWLEDGMENTS

This work was supported by NASA at Caltech under grants NNX8AI11G and NNX06AC21G, and under subcontract SA2715-26309 from UC Berkeley under NASA contract NAS5-03131; at JHU/APL by NASA grant NNX10AT75G, UC Berkeley subcontract SA4889-26309, and NSF SHINE grant 1156138; and

at NRL under grant NNH11AR711. We appreciate the availability of GOES data from NOAA, EPHIN data from the University of Kiel, and LASCO data from the Catholic University website.

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